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DYNAMIC MATERIAL PROPERTIES OF MOIST SAND

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The dynamic response of moist sand was measured under shock loading conditions similar to those produced by the ground shock loading from a conventional weapon. The loading was produced by a large bore (15 cm) light gas gun which produced shock stress levels of 1 to 3 KBar. The speed of propagation of the shock wave and the stress levels in the soil were measured directly by the use of Manganin gages.

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EXECUTIVE SUMMARY

The dynamic material response of sand, defined as the speed a strong shock wave propagates through the sand, and the attenuation of the shock as it propagates, was measured. The conditions were completely dry sand, and sand with varying degrees of water (moist sand). The goal was to determine the effect of water on the dynamic material response. Tests were conducted a shock strengths of one to three KiloBar, and with the water content varying from zero to 80 percent of the theoretical maximum.

All test were conducted in a 15 cm (6 inch) bore light gas gun. The gun was operated to give projectile speeds from 175 to 315 meters per second (m/s). This produced the desired shock loading of one to three KiloBar. The test specimen was 15 cm (5.5 inch) in diameter, and 2.5 cm (0.99 inch) thick. Specimen preparation consisted of mixing the water with the sand, and then compacting the mixture to the desired density. The normal stress verses time history of the incident shock and the shock leaving the test specimen were measured with Manganin normal stress gages using pulsed Whetstone bridges.

The results show very little dependence of the shock wave speed on moisture content. Both the incident shock strength and the leaving shock strength, for a given projectile speed, increased with the addition of moisture. However, there is considerable scatter of the data when moisture was added to the sand. The shock attenuation did not show a clear dependence on moisture, within the present test conditions, and the experimental scatter. The shock attenuation and shock speed in dry sand increased with shock strength.

PREFACE

This report was prepared by the Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, North Carolina 27695-7910, under contract No. F08635-89C-0141, for the Engineering and Services Laboratory, Air Force Engineering & Services Center AFESC/RDCM Tyndall AFB Fl 32403-6001.

This report summarized the work done between July 1989 and Oct 1990. The principal investigator at the North Carolina State University was F. Y. Sorrell, PhD of the Department of Mechanical and Aerospace Engineering, P. O. Box 7910, Raleigh, North Carolina 27695-7910. Capt. S. T. Kuennen and Mr. Walter Buchholtz served as the project officers for AFESC/RDCM.

This report has been reviewed by the Public Affairs office and is releasable to the National Information Service (NTIS). At NTIS it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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SECTION I
INTRODUCTION

A. OBJECTIVES

The primary objective of this program was to measure the dynamic material properties of moist soil subjected to shock loading similar to that experienced during the ground shock loading produced by a conventional weapon detonation. The ground shock loading was simulated by a large bore light gas gun, which could produce stress levels in the soil of 1 to 3 KBar. These stress levels are comparable with those occurring in the ground shock from a typical weapon. In addition, the bore of the gun is large enough that the soil samples can be tested in one-dimensional strain, and with a sample size that [illegible]e relative to soil heterogeniety. The speed of propagation and stress levels produced by a strong shock propagating through moist soil were measured directly during shock loading. These data were reduced to give the effect of moisture in the soil on initial shock strength, transmitted shock strength, shock wave speed, and shock attenuation. The purpose of these tests was to quantify the effect of soil moisture on the shock propagation and subsequent shock loading of buried structures. This is important because in most cases, it is not possible to design a hardened structure that will be protected by completely dry or saturated soil. Ultimately these data must be available before such structures can be designed to provide maximum protection from ground shock loading.

B. BACKGROUND

Most theoretical predictions of dynamic material properties of moist soil are based on a form of the rule of mixtures applied to a soil-water mixture, (Reference 1). This approach predicts a monotonic increase (or decrease) in property values from dry soil to water. Recent experimental results (Reference 2) have indicated that this approach may be overly simplified, and that the dynamic material properties of moist soil have considerably more variability than indicated by mixture. models. This presumably results from an interaction of the individual soil particles and water in such a way that the binding forces within the soil structure are altered or that additional forces arise. One such force that has been suggested is surface tension at water-soil and possibly at water-air interfaces. For example, Wu, et al. (Reference 3) demonstrated that surface tension can increase the dynamic shear modulus of soils by as much as a factor of two.

The dynamic material properties of moist soil are required to predict ground shock loading from weapons on hardened (buried) structures. However, such data at conditions applicable to ground shock loading from a near field detonation is very limited. Field test data are expensive and some important parameters, such as moisture content, are difficult to control. In addition, precision measurements are difficult to make under field conditions, and with field instrumentation. However, laboratory experiments are also difficult because relevant loading rates and magnitudes are so large that extensive facilities are required. In addition, modeling of the geological materials at large scale ratios (small models) is subject to scaling problems. This is because of the heterogeneous nature of soils. Indeed, the heterogeneous structure within the soil produces the variability of the dynamic material properties with moisture described above.

C. SCOPE/APPROACH

Because of the difficulties described above, the present test program was initiated, using a large bore light gas gun to shock load the test specimens. The large bore gun allows testing specimens of reasonable size, while still maintaining laboratory testing. Because the tests are conducted in laboratory conditions, the soil conditions and the shock properties can be accurately controlled and measured.

SECTION II
TEST PROGRAM AND FACILITY

This section describes the facility that was used for simulation of ground shock loading conditions, the preparation of the samples that were tested, and the instrumentation used to make the test measurements. Each of these is described in more detail in the following subsections.

A. TEST FACILITY

All tests were conducted in the 15 cm (6-inch) bore light gas gun located in the Department of Mechanical and Aerospace Engineering at N.C. State University. This facility was constructed for testing of geologic materials, in particular soils, at loading conditions similar to those produced by the ground shock from a weapon. The major advantages this facility offers to the present test program are the capability to produce stress levels representative of ground shock loading, and to produce a one-dimensional (uniaxial) state of strain. The 15 cm bore light gas gun facility is described in detail (Reference 4). A description of the use of this facility has also been reported (Reference 5). Some of the advantages of this technique are quantified briefly in the following discussion.

As previously mentioned, the simulation of ground shock loading conditions is difficult because of the rapid and high stress that is produced by a conventional weapon. The 15 cm light gas gun can produce accurately controlled high stress levels by selection of the projectile material and speed. Typically, stress levels of 1 to 3 KBar, and with rise times less than 20 microsecond were produced in moist soil test specimens. Moreover, prior test results have shown that test conditions are accurately controlled and repeatable. The capability to produce repeatable, high-stress loading in a laboratory is one of the main advantages of the light gas gun.

A simple, well-defined state of stress or strain is a necessity for an interpretation of the test data. The present tests utilize a test soil sample with a diameter of 15 cm, which is the maximum possible in which one-dimensional conditions can be produced with a 15 cm-bore gun. The test sample had a thickness of 2.5 cm for most tests. A diagram of the test configuration is shown in Figure 1. This sample configuration does not allow the release waves propagating in from the outer edge of the sample to have time to change the state of stress (or strain) that is produced as the incident shock propagates through the soil. Therefore the relatively thin test sample, which is confined in a sleeve, is in a state of uniaxial (one-dimensional) strain.

Impedance (stiffness) matching of the materials used for the projectile and cover plate required careful consideration. A thick projectile, made of a material which has a low shock speed was required to give a sufficiently long shock loading. After trying aluminum and lexan as projectile materials, Plexiglas was chosen as the projectile material used for the tests reported here. Aluminum had too a high shock speed, and lexan was too expensive for the desired projectile thickness. All tests were with a Plexiglas projectile 2.54 cm thick. The projectile is the moving layer at impact, and is referred to as the flyer. A cover plate is used to hold the soil in place and to provide a surface or layer on which the front gage can be mounted.

Matching of the impedance of the cover plate with the flyer and the soil requires a material close to the stiffness of both materials. If the cover plate is too stiff, it will unload rapidly, and the manganin gages at the interface will fail in tension. After a number of tests, a lexan cover plate was found to be the most satisfactory. The cover plate was 1.25 cm thick in all tests reported.

B. SAMPLE PREPARATION

Tests were be conducted on sandy soil, Eglin sand, which was acquired from Eglin Air Force, Florida, with varying moisture content. Grain size distribution was measured by a vibrating screen system, and found to be consistent with that reported by Ross (Reference 2). Three random samples were tested and all of them had the same size distribution. Moisture was added to produce the desired degree of saturation. The resulting sample was then compacted to the desired density, establishing the required density and degree of saturation. For the test specimens 2.5 cm thick, this compaction was done in three

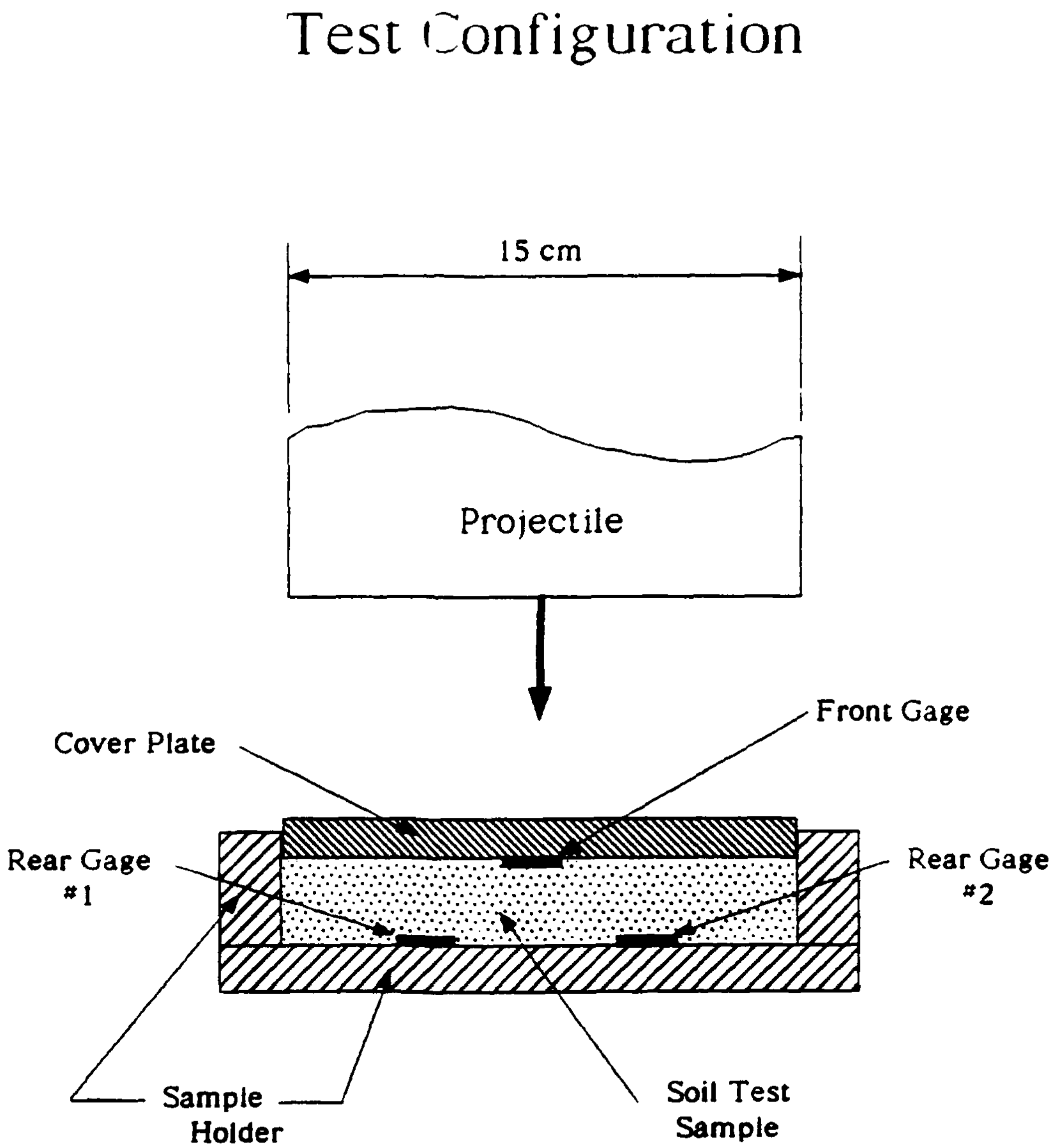

Figure 1. Test Configuration.

layers. The compaction was done in this way in an effort to assure that the moisture and density were uniform (homogeneous) throughout the specimen. This is basically the same procedure described by Reference 3.

As will be discussed in section III, experimental scatter in the data taken with a water and sand mixture (moist soil) was large. The sample preparation technique was repeatedly reviewed, and the procedure discussed with a number of people experienced in testing soil. It was suggested that all of the organic material be removed from the sand in an effort to remove scatter. Beginning with test K6-27, all of the organic material was screened from the test specimens before they were mixed with water and compacted.

Consideration was given to compacting the soil to the desired dry density, and then adding water after compaction. This method of sample preparation can result in different material properties when compared to sample preparation where the moist sample is compacted, as described above. Compaction of the moist soil was chosen as the most suitable method of sample preparation because it more closely represents the soil conditions that occur in the construction of a hardened structure.

C. INSTRUMENTATION

The instrumentation of the test specimen consisted of normal stress gages mounted at the front and the rear of the test sample. The location of these gages is shown in Figure 1. One of the major considerations in the test is to assure that the flyer impact is planar, i.e., that the flyer face in parallel with the cover plate. This is required to assure that the one-dimensional loading condition is achieved. Planar impact was determined by using two rear stress gages, as shown in Figure 1. The thickness of the gages is exaggerated in Figure 1 to show their positions. The gages are actually only 0.025 mm thick. Data in which the shock did not arrive at both rear gages at the same time were not used, because simultaneous arrival at both gages will occur if the impact is planar.

The normal stress gages were Manganin stress gages produce by Micro-Measurement Corporation. These gages respond to a change in normal stress by a change in the resistance of the gage. The change in gage resistance was measured by using each in one leg of a standard wheatstone bridge. Consequently, three bridge circuits were required. These gages are better suited to soil measurements than Carbon or Ytterbium. The Carbon gages were about a factor of 5 more expensive than the Manganin gages, and the Ytterbium were both more expensive and operate best at a range of stress levels that is larger than expected in the proposed tests. We have experience in using both Manganin and Carbon gages for shock measurements in soil; cost was the primary reason that Manganin gages were used. Because of the temperature dependence of these gages, they must be used in pulsed bridges which impose a current that heats them for only a short time. The present arrangement used pulsed bridges and bridge circuits manufactured by Dynasen, Inc.

In operation, the bridge voltage is initiated by a trigger circuit. The circuit operates by using the flyer to close an electrical contact as it impacts the cover plate. Contact closure then initiates the pulsed bridge circuit which supplies approximately 90 volts to the bridge for 200 microseconds. One of the difficulties in these type experiments, is the short time window that the bridge is operational. The test must be conducted during this time. The change in gage resistance was measured by the difference in voltage in the two legs of the bridge, which is a standard technique.

Data were taken using a four-channel analog to digital (A/D) data acquisition system. This system can take up to 500 K samples/s, or a sample every 2 microseconds. This sample rate was adequate for many of the tests, and always adequate for data taken from the rear gages. However, the flyer impact with the cover plate has a rise time of 4 to 12 microseconds. Consequently, this sample rate was not always fast enough to give an accurate picture of the stress verses time for the front gage. Therefore, data taken in the later experiments also used a high speed digital oscilloscope (DO) for data acquisition. The DO was set to sample at 20 MHz, which provided a sample every 50 nanoseconds. However, only two channels were available on the DO. In normal operation, data were taken from all three gages by the A/D system. At the same time data were recorded from the front gage and one of the rear gages by the DO. Sample normal stress vs time profiles as measured by both systems are given in Appendix A.

In addition to the normal stress, flyer speed at impact was also measured. This was accomplished by using a dual "velocity pin" technique. An electrical contact was closed by one set of velocity pins as the flyer passes. This contact closure was used to trigger, or start, a digital counter. Approximately 5 cm closer to the target a second set of pins was closed when the flyer passes them. Closure of the second set of pins was used to stop the counter. The elapsed time and distance between the two sets of pins was used to give the flyer speed. The system has been in use in the laboratory for a number of years, and has been improved until it is quite accurate and reliable. Projectile speed can be measured within $\pm$ 2 percent.

SECTION III
TEST RESULTS

All test results are summarized in Table 1. This table lists the test number, the measured projectile or flyer speed, and the moisture content in percent saturation. In addition, the computed initial peak stress gage is given. This is the peak stress that is expected to be measured by the front gage. Is is computed using the measured flyer speed and the computed soil impedance or stiffness. The soil stiffness was computed using the actual density of the mixture and the expected shock speed. The last three columns give the values measured by the normal stress gages. These are the peak input stress measured by the front gage, and the shock wave speed measured by the time elapsed between shock arrival at the front gage to the time of arrival at the rear gages. The peak transmitted stress, as measured by the rear gages, is given in the last column. As can be seen in this table, the moisture content varied from dry sand (0 percent moisture) to 80 percent of the maximum amount of water theoretically possible. It was found that 80 percent saturation was the maximum amount of water that it was practical to add to the sand and still maintain a reasonably homogeneous mixture. At higher saturations, sufficient water was emitted upon compaction that the percent saturation could not be determined. One test, K6-33, was conducted on pure water. This was to validate the experimental technique by comparing shock magnitude and speed expected in water where the material properties are accurately known, with those measured in the present facility. The comparison gave expected values for peak stress and wave speed, and lends confidence to the present experimental technique.

The data given in Table 1 begin with test K6-11. This was because the first 10 tests were used in determining the proper flyer (projectile) and cover plate materials, and in debugging the instrumentation. Of the tests given in Table 1, the following are considered invalid. A check of the time of shock arrival at the two rear gages indicated non-planar impact on tests K6-16, K6-24 and K6-26. Moreover, one of the rear gages failed in tests K6-20 and K6-22, and thus planar impact could not be assured. The shock wave speed in tests K6-17 and K6-18 was not reasonable, probably because of stratification of the water in the test sample. These were the first tests at high saturation and the sample was compacted in one layer.

TABLE 1. DYNAMICS OF MOIST SOIL - DATA SUMMARY

Shot No.	Flyer Speed (m/s)	Water Cont (%Sat)	Predict Stress(3) (KBar)	Measured Values: Peak Input Stress (KBar)	Measured Values: Shock Wave Speed (m/s)	Measured Values: Peak Trans Stress (KBar)
K6-11	166	0	1.1	1.03	610	0.33
K6-12	205	0	1.35	1.34	599	0.59
K6-13(5)	202	50	2.05	(1)	605	
K6-14	207	50	2.09	2.05	578	0.63
K6-15	200	50	1.84	3.2	508	0.45
K6-16(2)	160	25	1.46	2.56	530	0.27
K6-17	188	75	2.17	2.57	1270	0.3
K6-18(4)	203	80	2.54	2.52	2900	0.5
K6-19	205	0	1.35	1.2	640	0.41
K6-20(2)	203	50	2.36	2.22	705	0.34
K6-21	207	50	2.08	2.9	577	0.46
K6-22(2)	149	75	1.78	1.76	706	0.27
K6-23(5)	208	75	2.24	(1)	605	
K6-24	208	75	2.4	.9?	668	
K6-25	212	50	2.41	1.5	680	0.65
K6-26(2)	185	0	1.46	7.8		
K6-27	175	25	1.69	3.42	577	0.6
K6-28	208	25	2.1	3.09	604	0.59
K6-29(4)	215	80	2.5	2.64	668	1.46
K6-30	318	0	2.3	2.1	747	1.5
K6-31	314	15	4.4	3.2	668	1.74
K6-32	208	15	1.98	1.5	577	0.6
K6-33	203	Water	2.42	2.16	1411	1.8
K6-34(4)	213	80	2.1	2.34	530	1.4
K6-35	215	15	1.88	1.53	596	0.68

Notes:

(1) Data file Lost
(2) Impact may not have been planar
(3) Impedance used to predict stress = (mixture density) × (wave speed)
(4) Max %Sat Practical
(5) Speed Estimated

Subsequent tests were with the sample compacted in three layers. The data file was lost in tests K6-13 and K6-23. In these tests the shock speed was estimated from the raw oscilloscope trace, but the peak stress at either the front or the rear gages was not recorded. Consequently, for the shock strength data, tests 13, 16, 17, 18, 20, 22, 23, 24, and 26 were omitted. The data set consists of the remaining tests in Table 1.

In addition to varying moisture content, the flyer speed was also varied. Most of the tests were conducted at a flyer speed of 200 meters per second (m/s) to give a complete data set at one loading condition. This was especially true when it was found that the data had more scatter than expected, and hence additional tests at this loading condition were needed to validate any trend in the data. Subsequently, the test condition with a flyer speed of 200 m/s was chosen for most of the data. However, limited data were also taken at a flyer speed less than 200 m/s, usually around 175 m/s. At the lower speeds, the friction between the barrel and the projectile becomes more important, and the projectile speed can not be controlled as accurately. Two tests with a flyer speed of approximately 315 m/s, tests K6-30 and K6-31, were also conducted.

The results are presented in graphical form in Figures 2 - 6. A brief description of each graph are given here. In all of these graphs the test number is given just to the right each data point. The first three graphs, Figures 2 - 4, are for the test conditions of a flyer speed of 200 m/s. These data are thus for a constant shock loading condition. Figure 2 shows the initial input peak stress, as measured by the front gage, as a function of moisture content. For a constant flyer speed, a higher sand impedance, or a greater sand stiffness, will result in a greater peak stress being input from the flyer and cover plate to the sand. This is clearly evident in Figure 2, where the input peak stress rapidly rises when moisture is added to the soil.

Figure 3 gives the transmitted peak stress, as measured by the rear gages, as a function of moisture content for a 200 m/s flyer. Again there is an increase in transmitted peak stress as the soil becomes stiffer. However, this increase is not as large as the input peak stress shown in Figure 2. The transmitted peak stress increases only slightly until a high water content, 75% saturation or higher, is reached. At the high water content the transmitted peak stress is around a factor of three larger than the dry sand.

Figure 4 gives the shock wave speed through the sand for the data with a flyer speed of 200 m/s, as a function of soil moisture. There is considerable scatter in these data, and no clear dependence of shock speed on moisture content is evident. This is also true if all of the valid data in table 1 are plotted together. However, there is a clear dependence of shock wave speed on the stress level. In order to illustrate this, the shock wave speed in dry sand was plotted as a function of flyer speed. These data are given in Figure 5, and clearly show increasing shock speed with flyer speed or stress. This is to be expected at the higher stress levels, where the material response is non-linear.

One of the major concerns is with the shock attenuation, or the ratio of peak shock stress transmitted through the soil to the peak stress input to the soil. In the present configuration, this is the ratio of peak stress measured by the rear gages to the peak stress measured by the front gage. These data are plotted in Figure 6, for all valid data given in Table 1. Unfortunately, these have the greatest scatter and within this scatter there is no clear dependence on the moisture content of the soil. As with shock speed, there is however, a clear dependence of shock attenuation on stress level. Shock attenuation in dry soil vs flyer speed is plotted in Figure 7. As stated, there is a clear dependence of shock attenuation on flyer speed or stress level, with the higher stress levels having less shock attenuation. This observation raises questions as to the validity of data taken a low stress levels to the assessment of dynamic soil properties at higher stress levels typical of that produced by the ground shock from conventional weapons.

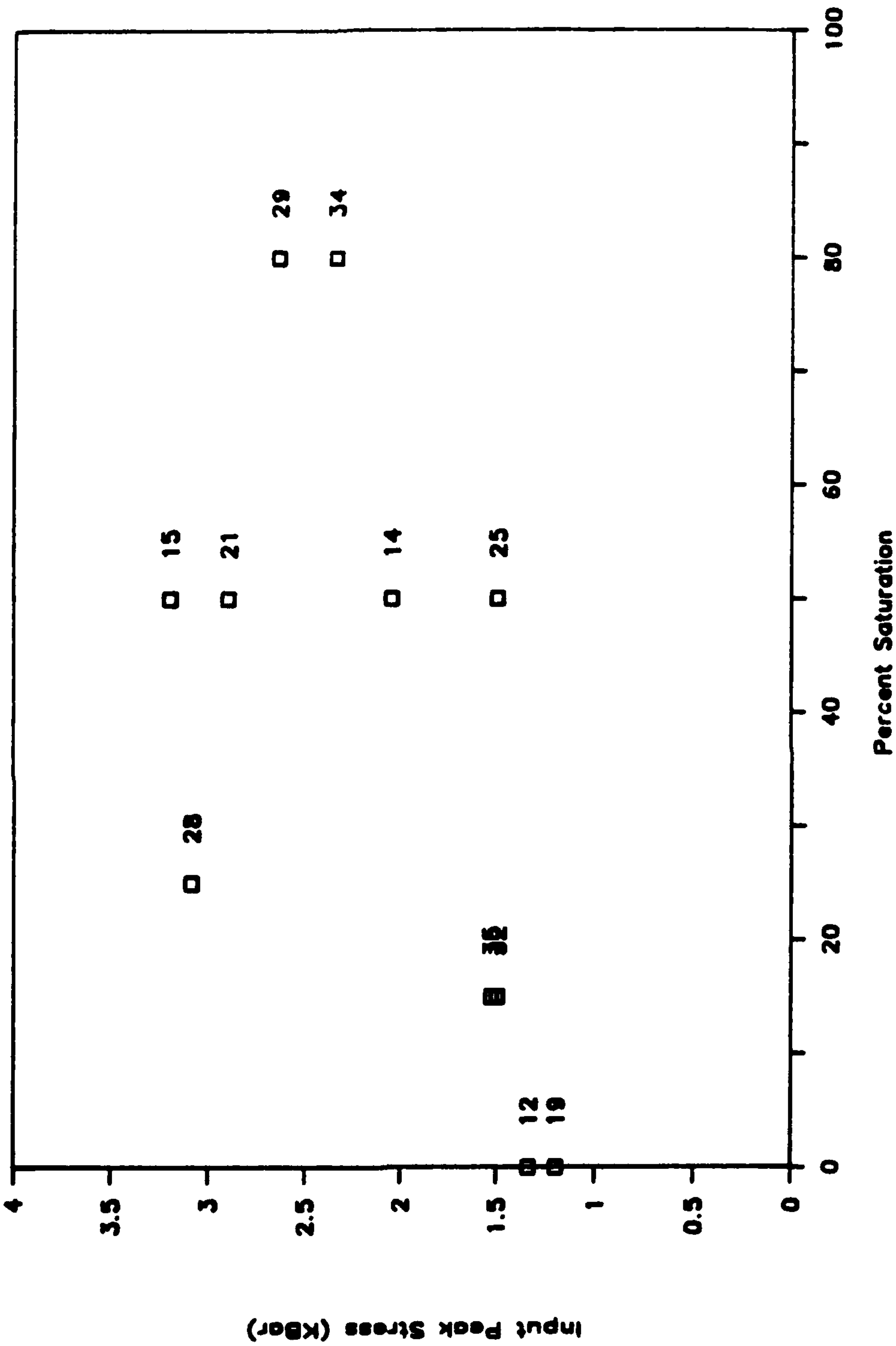

Figure 2. Input Peak Stress – 200 m/s Flyer

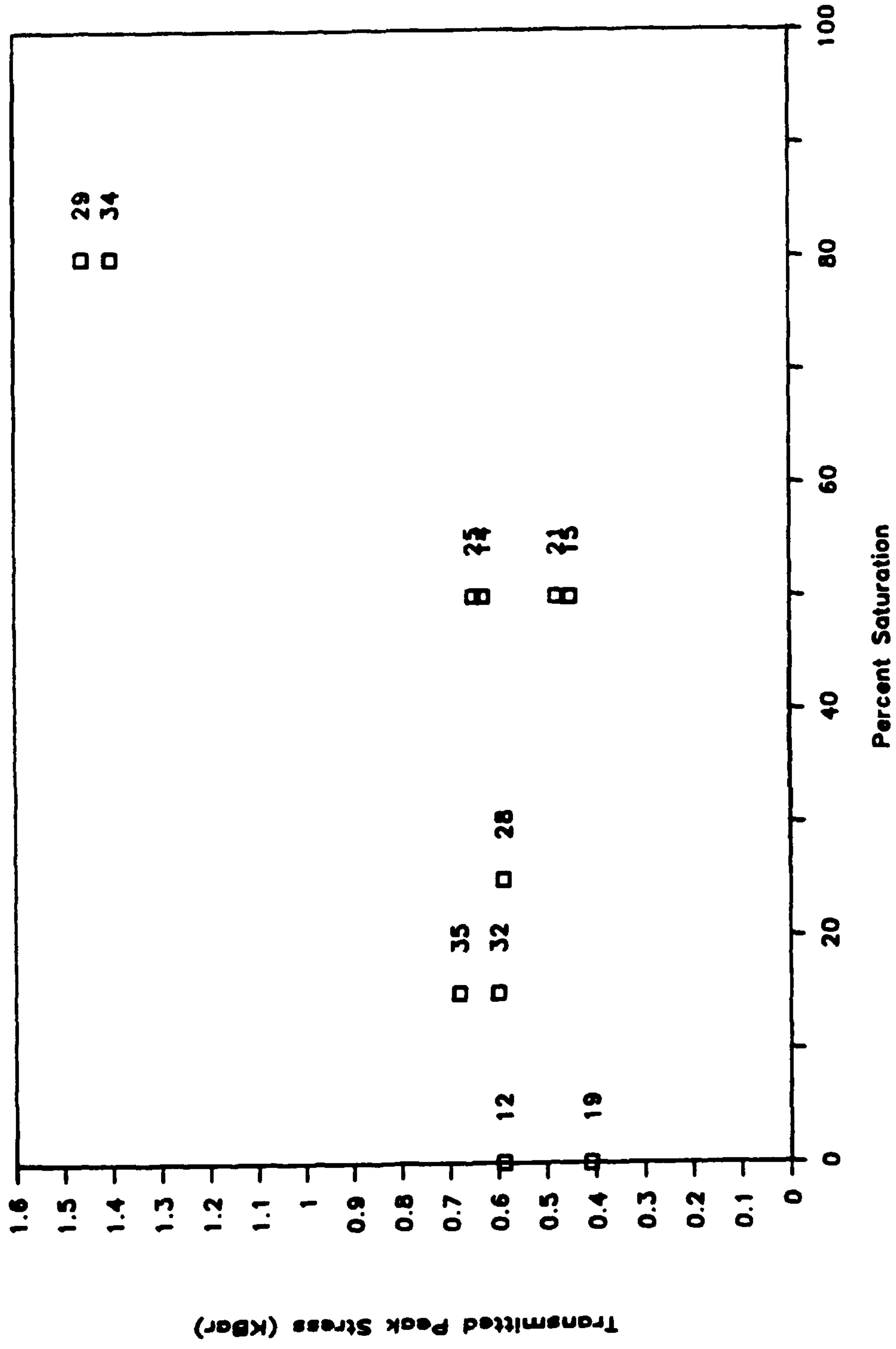

Figure 3. Transmitted Peak Stress - 200 m/s Flyer

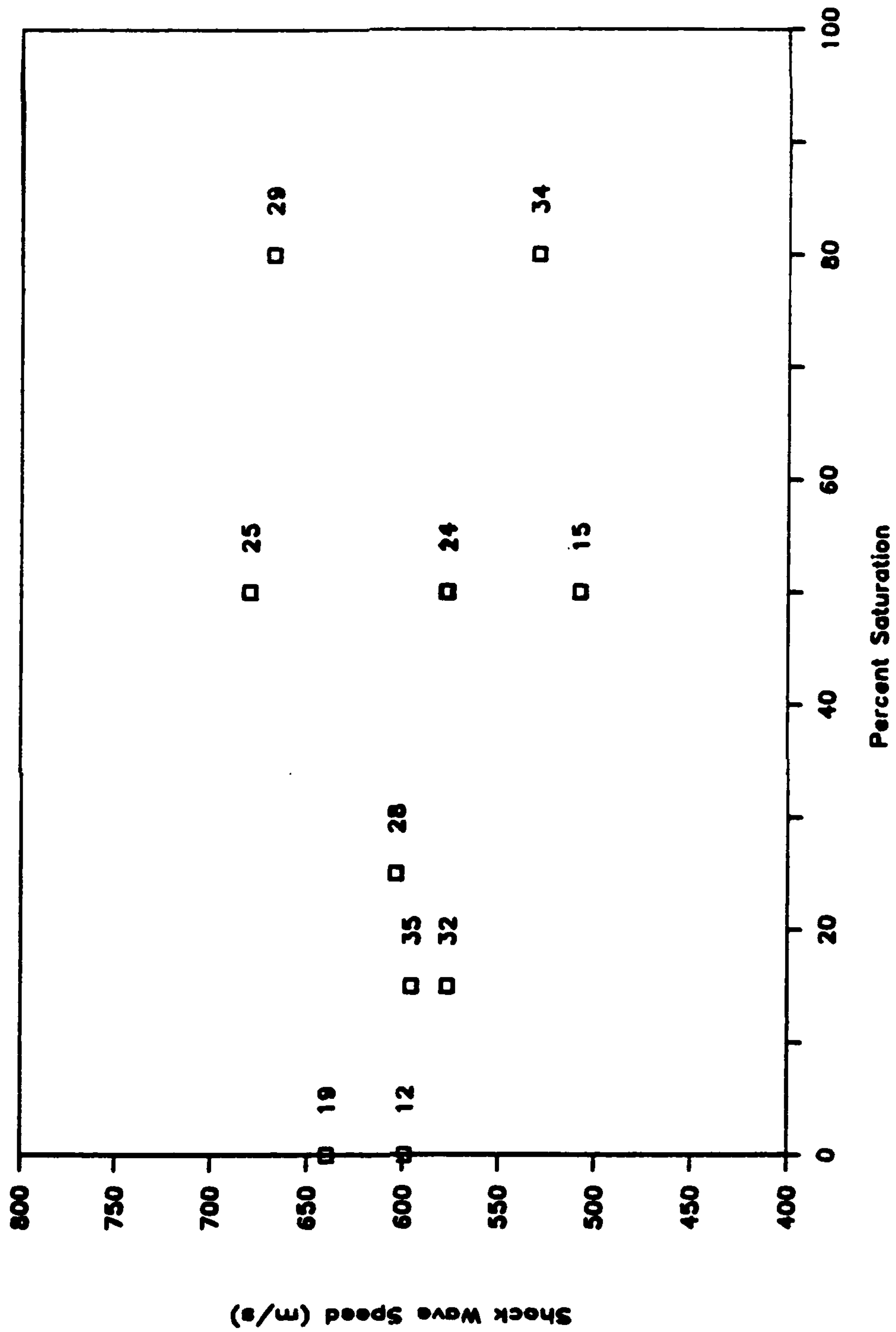

Figure 4. Shock Wave Speed – 200 m/s Flyer

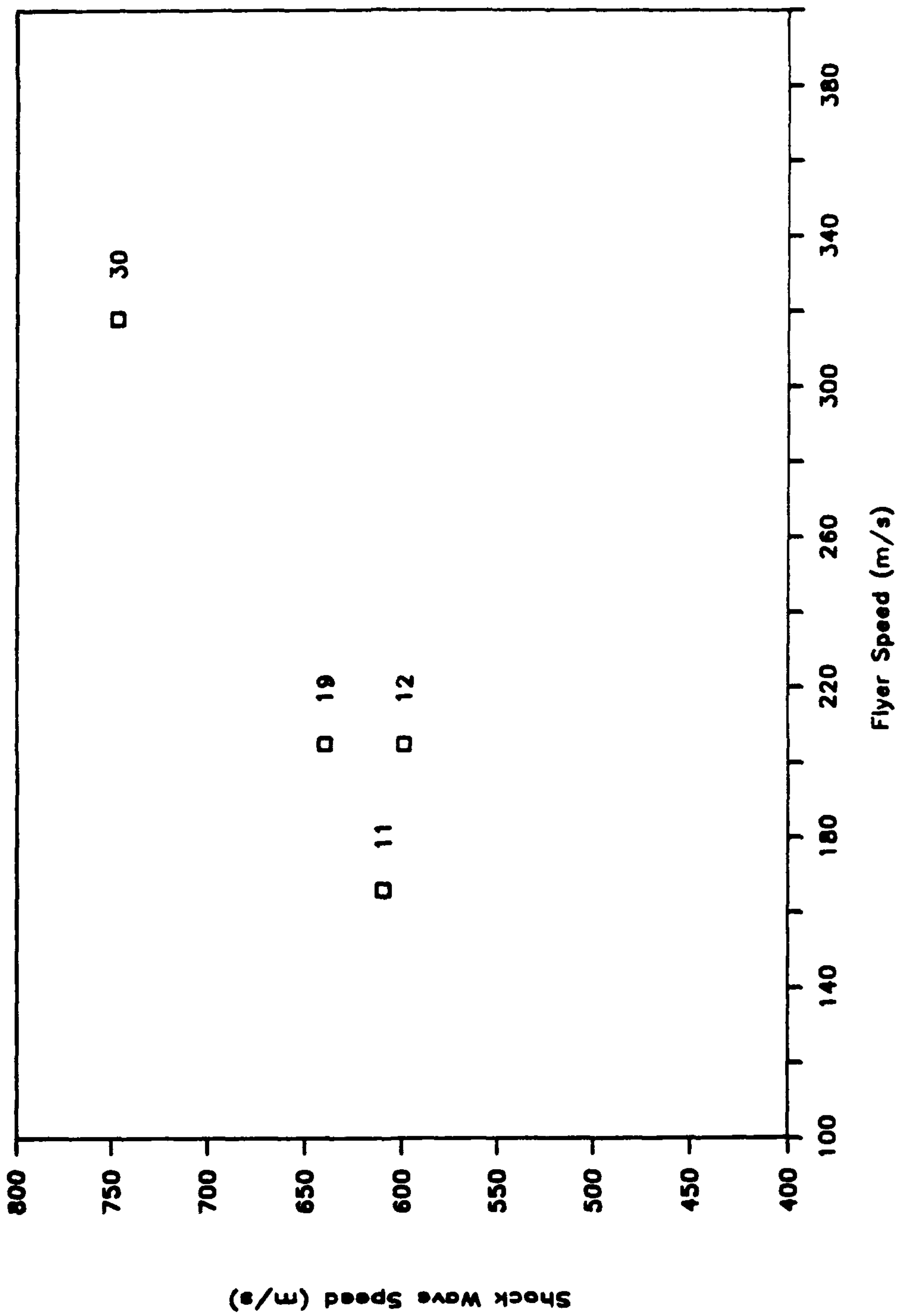

Figure 5. Shock Wave Speed in Dry Soil

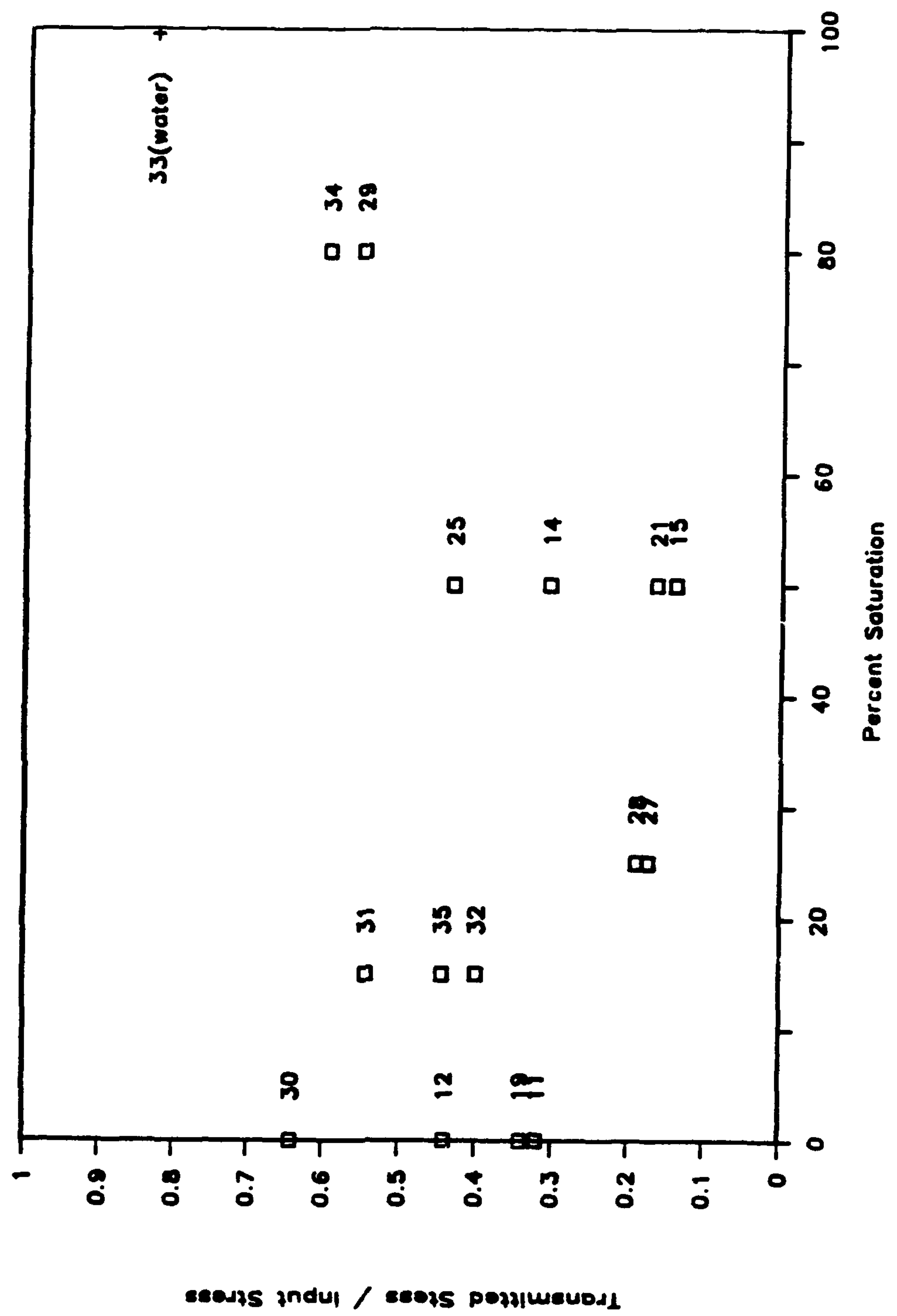

Figure 6. Transmitted/Input Peak Stress Ratio

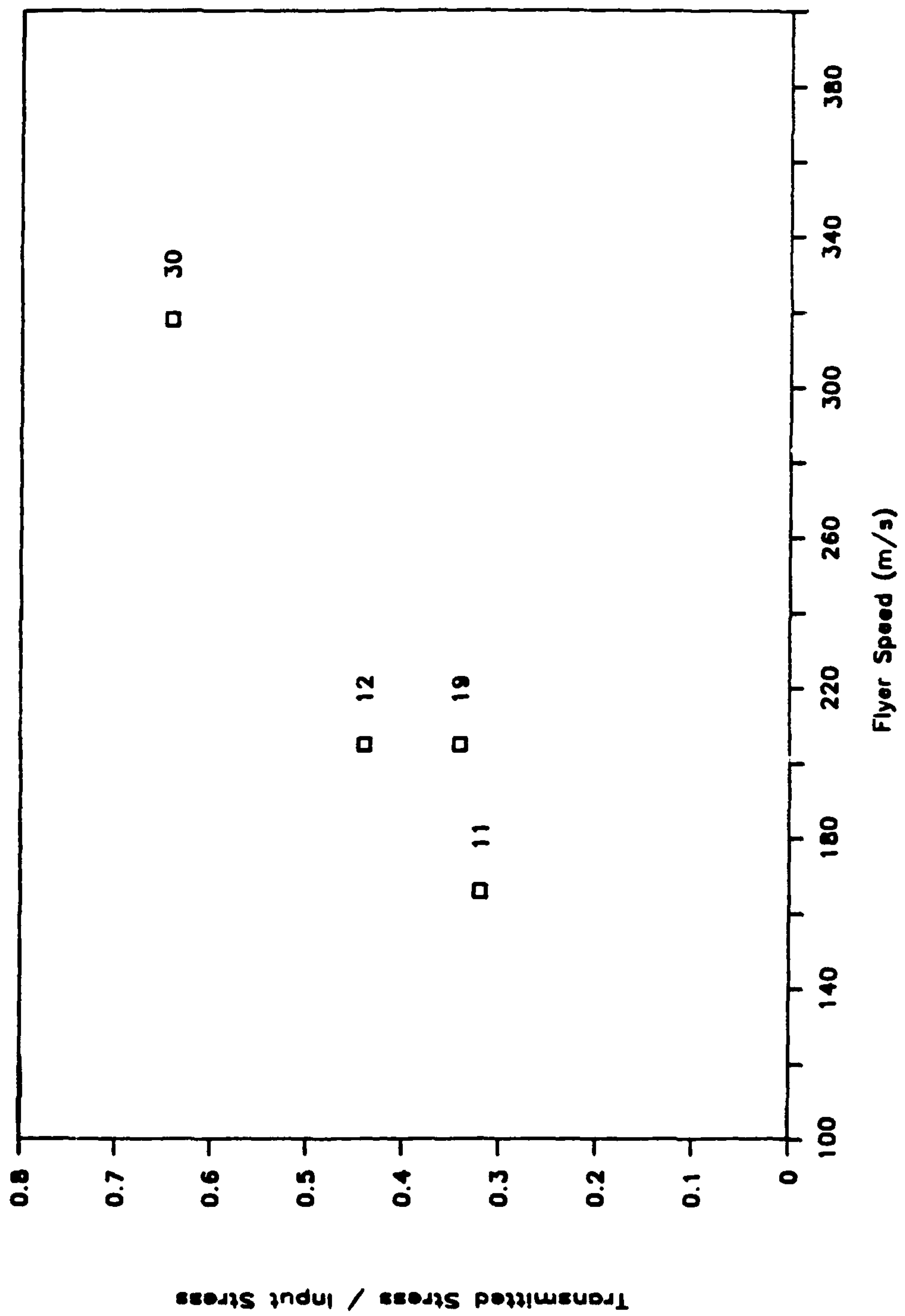

Figure 7 Shock Attenuation in Dry Soil

SECTION IV
SUMMARY AND CONCLUSIONS

A review of the data shows a considerable amount of scatter, particularly for those data taken with a mixture of water and sand (moist soil). A number of changes were initiated in the way the test specimen was prepared to reduce the scatter. For example, although the specimen is thin, the sample was compacted in three layers. Another approach was to remove all organic material from the test specimen. It is repeated here that a size distribution was made on three random samples, and that they were identical with each other and with that reported in Reference 2. Even with these precautions, the scatter in the data for moist soil is large. Clearly, the scatter may mask some features that might be present. Within the scatter present in the data, the following conclusions were reached.

1. There is a sharp increase in peak input stress with water content in the sand. This occurs at very low moisture levels and with a constant flyer speed or input shock loading. This is illustrated in Figure 2.

2. There is an increase in transmitted peak stress with moisture content, however this does not become significant until high levels of saturation are reached. This is illustrated in Figure 3.

3. Within the experimental scatter and the present stress levels, there is no dependence of shock wave speed on moisture content. This is illustrated in Figure 4.

4. The shock attenuation, which is defined as the ratio of peak transmitted stress to peak input stress, does not depend on moisture content. This is a factor of importance, and unfortunately these data have the largest scatter. However, within the scatter there is no apparent dependence of shock attenuation on moisture content. This is illustrated in Figure 6.

5. In dry soil there is a well-defined dependence of both shock wave speed and shock attenuation on stress level. Shock wave speed increases and shock attenuation decreases with increasing flyer speed or stress level. These data in dry soil have less scatter than the data taken in moist soil. This is illustrated in Figures 5 and 7.

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APPENDIX

Sample time histories of measured normal stress vs time.

A-1 Normal Stress vs Time for Test K6-12, Data from A/D Data Acquisition System. (Digital Oscilloscope not available)

A-2. Normal Stress vs Time for Test K6-28, Data from A/D Data Acquisition System.

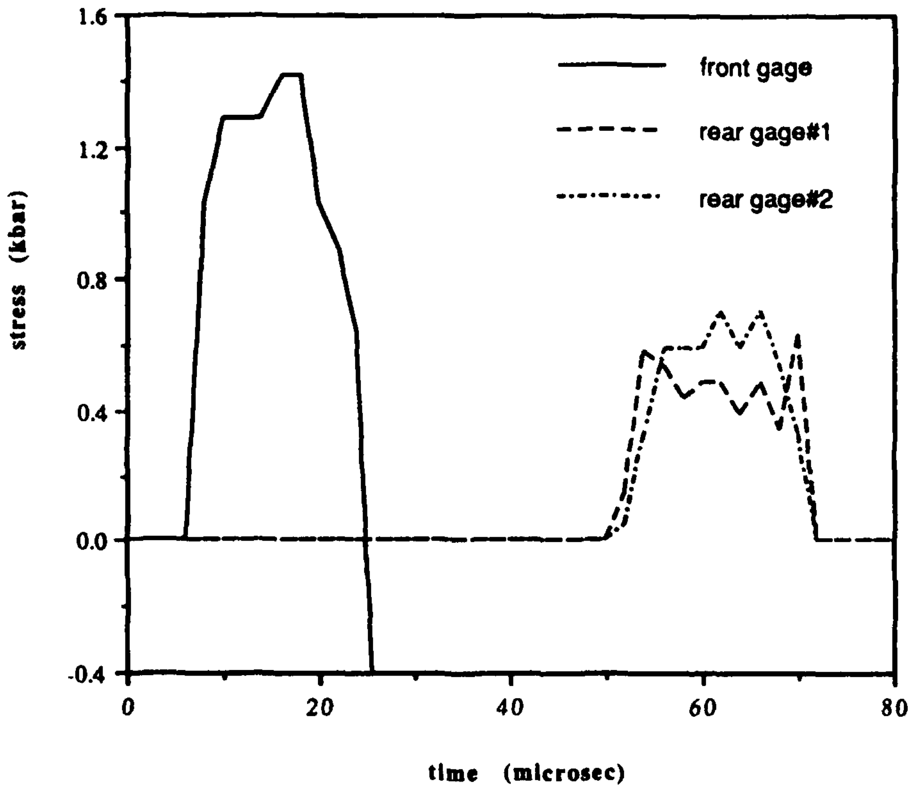
A-3. Normal Stress vs Time for Test K6-28, Data from Digital Oscilloscope.

A-4. Normal Stress vs Time for Test K6-30, Data from A/D Data Acquisition System.

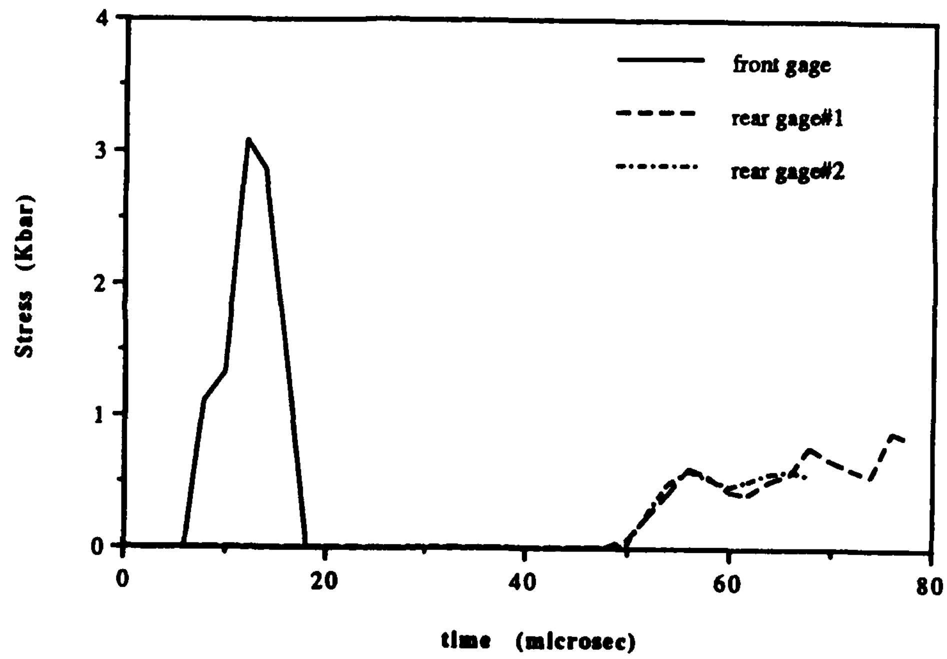
A-5. Normal Stress vs Time for Test K6-30, Data from Digital Oscilloscope.

A-6. Normal Stress vs Time for Test K6-34, Data from A/D Data Acquisition System.

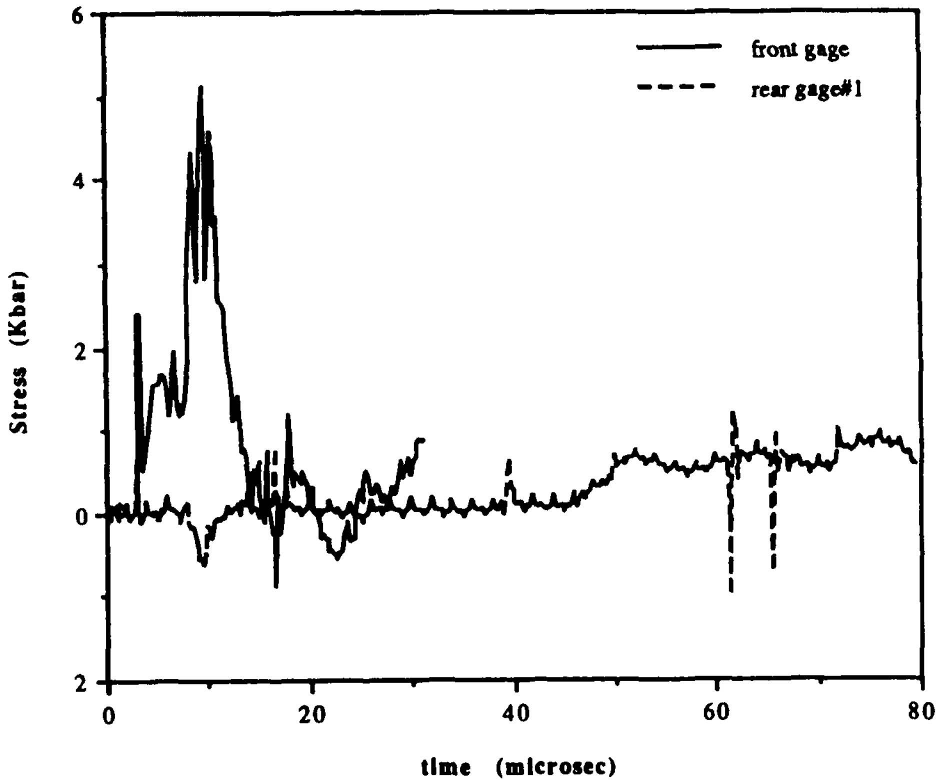
A-7. Normal Stress vs Time for Test K6-34, Data from Digital Oscilloscope.



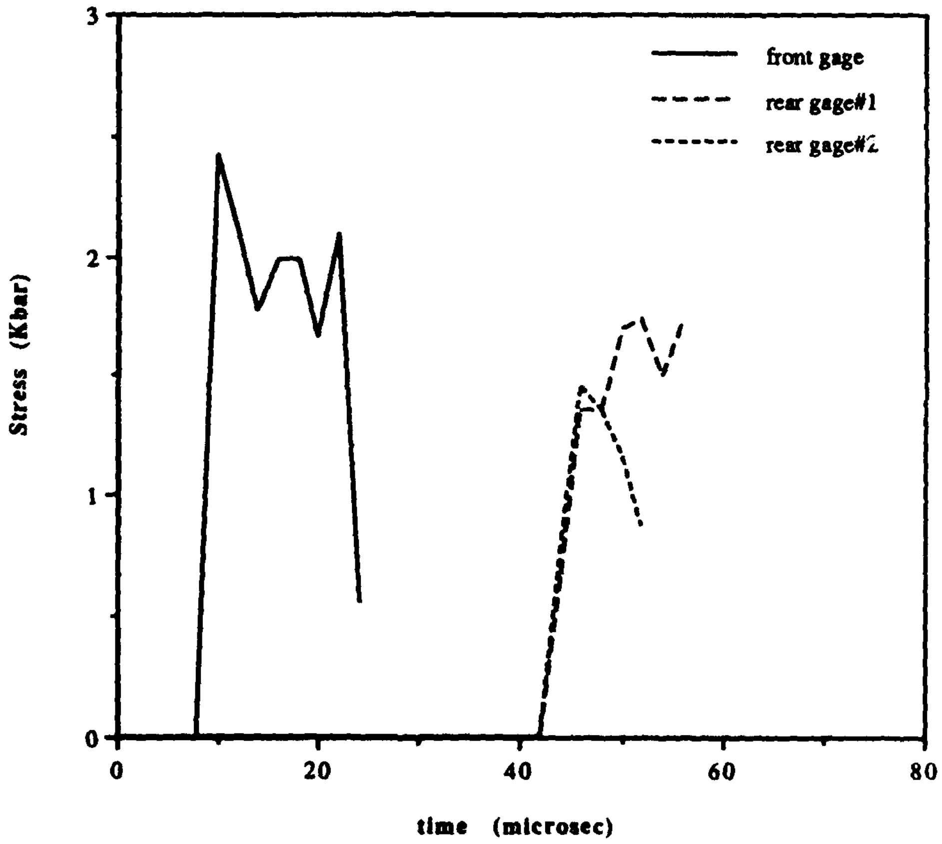
A-1 Normal Stress vs Time for Test K6-12, Data from A/D Data Acquisition System. (Digital Oscilloscope not available)



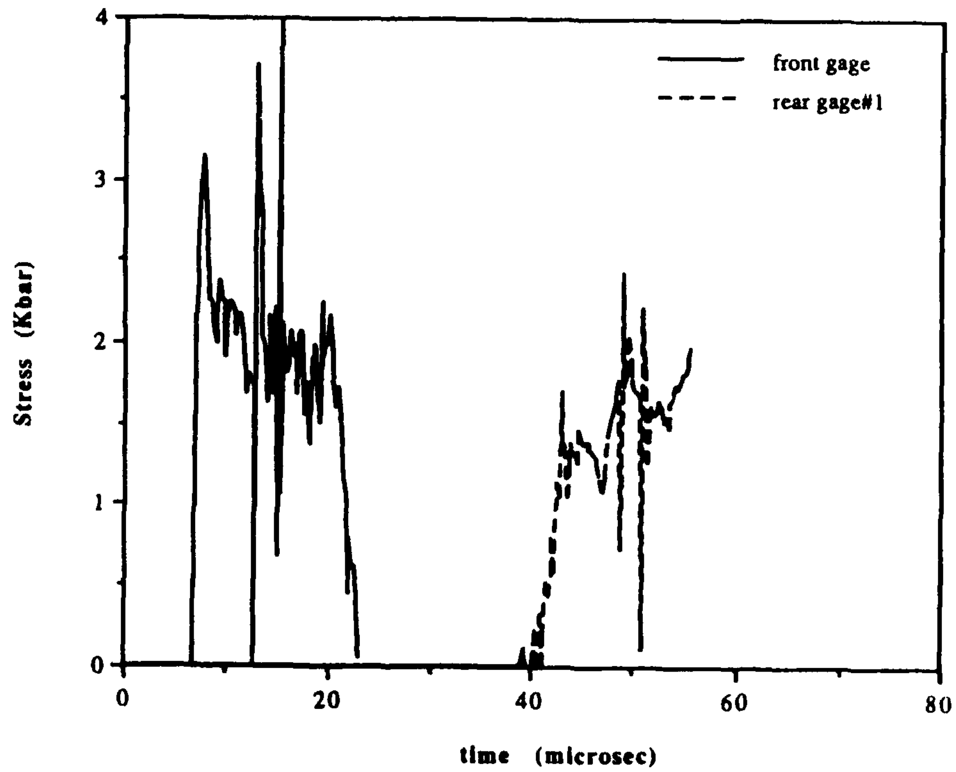
A-2. Normal Stress vs Time for Test K6-28, Data from A/D Data Acquisition System.



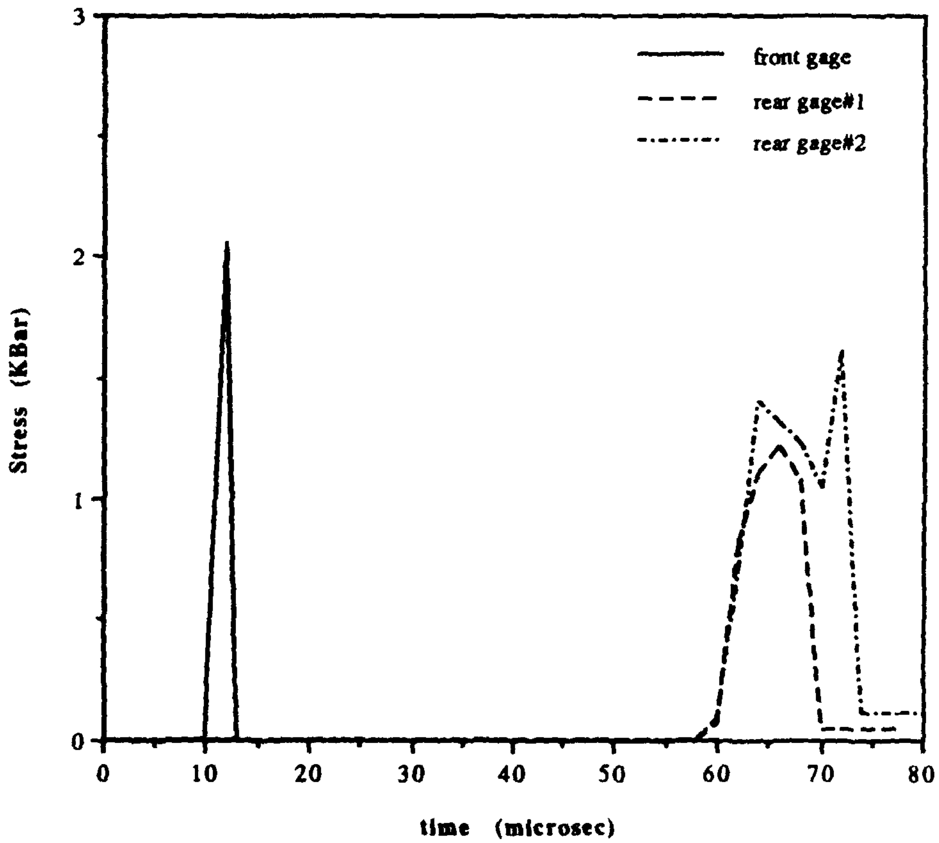
A-3. Normal Stress vs Time for Test K6-28, Data from Digital Oscilloscope.



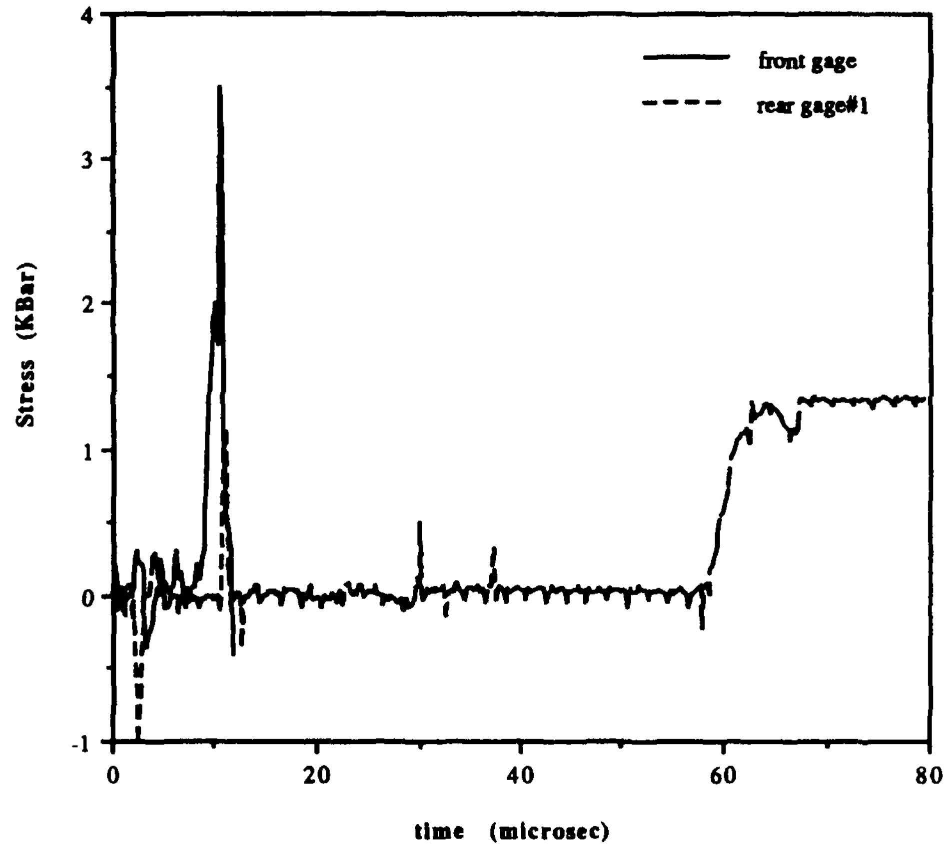
A-4. Normal Stress vs Time for Test K6-30, Data from A/D Data Acquisition System.



A-5. Normal Stress vs Time for Test K6-30, Data from Digital Oscilloscope.



A-6. Normal Stress vs Time for Test K6-34, Data from A/D Data Acquisition System.



A-7. Normal Stress vs Time for Test K6-34, Data from Digital Oscilloscope.